APPLICATION OF OBJECTIVE FUNCTIONS FOR THE OPTIMAL FILTER DESGIN FOR HVDC INVERTER

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Abstract

Transient and static characteristics of HVDC inverter can be analyzed with various simulation tools. For the optimal filter design, various performance criteria are proposed. In this paper, performance index is calculated based on proposed per phase equivalent circuit. Voltage and harmonic and filter power loss are selected as criteria. Optimization procedure is performed to find optimal passive filter parameters. Dynamic characteristic is also analyzed with proposed equivalent circuit.

1. Introduction

HVDC transmission has many advantages in environmental and economic aspects comparing with AC transmission. By adopting DC transmission system stability and reliability of power system can be improved. But harmonics can be generated from HVDC inverter and reactive power also should be compensated. HVDC inverter converts DC power to AC power. Conversion process mostly done by thyristor switching and line commutation is used. Therefore for the stable DC/AC conversion, voltage of AC bus should be stable.

To eliminate generated harmonics, passive filter is widely used due to its simple structure and economical merit. Recently as high voltage and power switching devices are developed, use of active filter is considered. Active filter has excellent harmonic characteristic during load variation. But implementation in actual power system requires further research.

To design passive filter for the HVDC system. system characteristics should be analyzed first. Particularly system harmonics or performance index to optimize system capacity should be defined and it can be calculated with equivalent circuit. Optimal filter parameters can be varied depending on performance index. Selection of performance index is very difficult due to its nonlinear characteristics. For optimization, application of analytic function has limitation.

Among available performance index which is adopted in various design procedure, voltage harmonics comparing with ac reference voltage and power loss are selected as performance index. Performance index is calculated with proposed per phase equivalent circuit and optimal parameters are obtained by optimization technique. Dynamic characteristics are also analyzed with proposed equivalent circuit.

2. Characteristic of HVDC system

Basic composition of AC/HVDC system is shown in Fig. 1. HVDC inverter system consists of 12 step thyristor inverter, snubber, Y-Y, Y-Δ connected transformer, capacitor bank for reactive power compensation, filter for harmonic rejection and controller and DC power controller. DC power is controlled by switching signal from controller. Generator bus is represented by equivalent voltage source and impedance. Transmission line and load are represented by resistance and inductance.

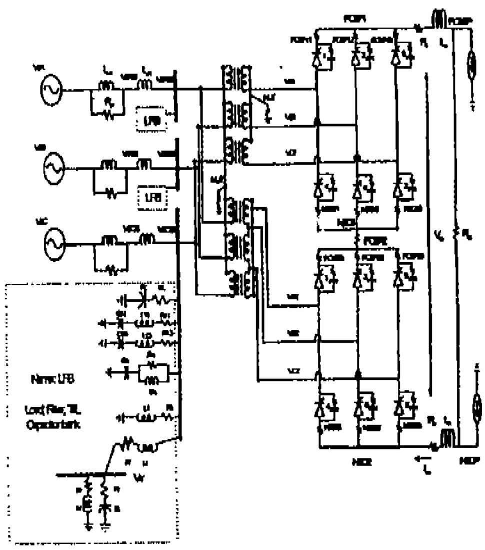

Fig.1 12 Pulse HVDC inverter system connected to power system

3. Filter design characteristic

During inverter operation, voltage and current harmonic exist both AC and DC side. If the number of pulse of converter is p, it generates pq-th and (pg ±1)-th harmonics. here, q=1,2,3....... Amplitude of harmonic is decreased as order of harmonic is increased. In case of 12 pulse converter, harmonic component of AC side is n=11,13,15. To decrease harmonic component ac filter should be used. In most cases, AC filter is installed in source side of transformer.

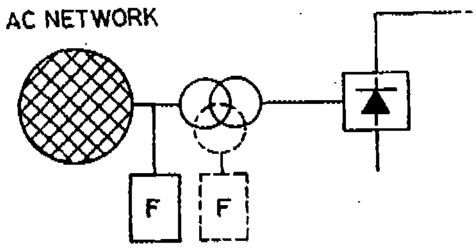

Fig. 2. AC filter connection

Parameters which effects on harmonic generation are as follows.
(1) Converter delay angle
(2) Converter control strategy
(3) Electrical load
(4) Capacitor bank
(5) AC/DC link stiffness

Many harmonic rejection techniques are proposed. Variation of filter configuration is one of them. Gilsig proposed a filter configuration which replaces resistor of each filter with one resistor. Even though filter loss can be decreased, harmonic component is almost same.

For the stable converter operation, detecting source voltage of converter is necessary. Since actual source voltage is not perfect sinusoidal, direct sensing is difficult due to reactance voltage drop. Compensation is needed.

4. Selection of performance index

To eliminate generated harmonics, passive filter is widely used due to its simple structure and economical merit. Recently as high voltage and power switching devices developed, use of active filter is considered. Active filter has excellent harmonic characteristic during load variation. But implementation in actual power system requires further research.

For the general filter design, practical criteria is to keep certain harmonic component under certain value. Harmonic current and voltage can be criteria. Harmonic voltage is widely used in filter design since limitation on voltage harmonic is much easier than limitation on current harmonic of ac network due to impedance variation.

In filter design, current source, filter admittance and system admittance should considered in detail. Current source is changed by load variation and firing angle variation. For voltage harmonic, Fig. 3 is used.

Most of tuned filter consists of RLC and it is tuned to specific harmonic component. Impedane at resonant frequence(fn) is R. To select R,L,C there are two basic parameters, quality factor(Q) and reactive frequency deviation(δ)

Filter impedance is a function of Q and δ.

$$Z_1 = R + j(wL - \frac{1}{wC}) \tag{1}$$

$$w = w_n(1+\delta) \tag{2}$$

$$w_n = \frac{1}{\sqrt{LC}} \tag{3}$$

Resonant frequency is

$$X_0 = w_n L = \frac{1}{w_n C} = \sqrt{\frac{L}{C}} \tag{4}$$

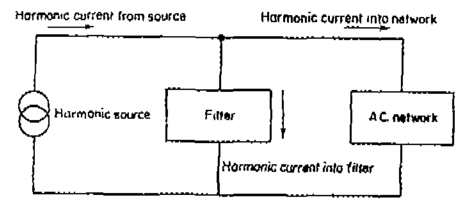

Fig. 3. Circuit for calculation of voltage harmonic

Reactance of inductor and capacitor at resonant frequency is

$$Q = \frac{X_0}{R} \tag{5}$$

$$C = \frac{1}{w_n x_0} = \frac{1}{w_n R Q} \tag{6}$$

$$L = \frac{X_0}{w_n} = \frac{RQ}{w_n} \tag{7}$$

If (2)(6)(7) are substituted into (1)

$$Z_f = R(1 + jQ\delta(\frac{2+\delta}{1+\delta})) \tag{8}$$

or since δ is less than 1

$$Z_f \simeq = R(1 + j2\delta Q) = X_0(Q^{-1} + j2\delta) \tag{9}$$

and

$$|Z_f| \simeq R(1 + 4\delta^2 Q^2)^{1/2} \tag{10}$$

Admittance is

$$Y_f \simeq \frac{1}{R(1+2\delta Q)} = G_f + jB_f \tag{11}$$

Here

$$G_f = \frac{Q}{X_0(1+4\delta^2 Q^2)} \tag{12}$$

$$B_f = -\frac{2\delta Q^2}{X_0(1+4\delta^2 Q^2)} \tag{13}$$

Voltage harmonic is

$$V_n = \frac{I_n}{Y_{nf} + Y_{sn}} = \frac{I_n}{Y_n} \tag{14}$$

Therefore to decrease voltage harmonic, total admittance of filter should be increased. Also, increase of voltage harmonic effects on the voltage sensing which is needed to determine reference point of firing angle. It also effects on system stability. Purpose of optimized filter is to minimize voltage harmonics at AC bus. But to get AC voltage, load flow equation should be solved .

Another aspects in determining performance index is power loss generated in filter. If Q is large, following assumption is possible.

$$V_c = V_L + V_s \tag{15}$$

Here V_c, V_L, V_s are capacitor, inductor, supply voltage respectively.

Filter size is represented as follows.

$$SIZE, S = \frac{V_s^2}{X_c - X_L} \tag{16}$$

Here X_c, X_L are fundamental reactance of capacitor and inductor.

If filter is tuned to n-th harmonic

$$X_0 = nX_L = X_c/n \tag{17}$$

i.e. $X_L = X_c/n^2, V_L = V_c/n^2$

Therefore,,

$$S = V_s^2/[X_c(1-1/n^2)] = (V_s^2/X_c)[n^2/(n^2-1)]MVAr \tag{18}$$

and

$$V_c - V_L = V_c(1-1/n^2) = V_s \tag{19}$$

i.e., $V_c = [n^2/(n^2-1)]\, V_s \;\; kV$

Power loss of capacitor is the sum of fundamental and harmonic component and they are represented as follows.

Fundamental component :

$$V_c^2/X_c = (V_s^2/X_c)[n^2/(n^2-1)]^2 \text{MVAr} \tag{20}$$

$$= S[n^2/(n^2-1)] \text{MVAr} \tag{21}$$

Harmonic component :

$$I_n^2(X_c/n) = [(I_n^2 V_s^2)/(Sn)][n^2/(n^2-1)] \text{MVAr} \tag{22}$$

Total power loss :

$$K_{CL}[S + (I_n^2 V_s^2)/(Sn)][n^2/(n^2-1)] \text{MVAr} \tag{23}$$

Here K_{CL} is capacitor loss factor (kW / MVAr)

Inductor loss is as follows :

Fundamental component :

$$V_L^2/X_L = (V_c/n^2)^2(n^2/X_c) = V_c^2/n^2 X_C \tag{24}$$

$$= (S/n^2)[n^2/(n^2-1)] \text{MVAr} \tag{25}$$

Reactance at resonant frequency is same as that of capacitor.

Above procedure is conventional filter design procedure. Recently many performance criteria is used in various application. Saied et. al used current THD(Total Harmonic distortion) after calculation of each harmonic current on each harmonic impedance. Ashton et.al proposed the concept of active power line conditioner and use RMS error between reference voltage and actual voltage. Grady et. proposed four performance index.

1. Total Harmonic Distortion(THD)
2. Telephone Influence Factor(TIF)
3. Motor Load Loss Function(MLL)
4. Single-Bus Sine Wave Correction

It can be represented by following equations.

At certain bus k :

$$THD_k = \frac{\sqrt{\sum_{h=2}^{H} |V_k^h|^2}}{|V_k^1|} \tag{26}$$

$$TIF_k = \frac{\sqrt{\sum_{h=1}^{H} (|V_k^h| W_h)^2}}{|V_k(rms)|} \tag{27}$$

$$(MLL_k)^2 = \frac{1}{|V_k^1|} \sum_{h=2}^{H} \frac{|V_k^h|^2}{h} \tag{28}$$

$$f(I_m) = \sum_{h=2}^{H} |V_m^h|^2 \tag{29}$$

In this paper, voltage harmonic and power selected as performance index and optimization procedure is performed.

5. System modelling for calculation of performance index

5.1 Equivalent circuit

With the result of load flow calculation, voltage at load bus and infinite bus can be calculated. Voltage at load bus is fed back to controller and it is used as reference voltage. Therefore harmonics contained in sensed voltage greatly affects on the stability of inverter. So, it is necessary to calculate total harmonics contained in sensed voltage compared with infinite bus.

In most of HVDC inverter, harmonic elimination is carried out by the passive filter. Voltage harmonics are influenced by filter characteristics. But calculation of voltage harmonics is not a easy task with EMTP simulation, since it is mainly used to analyze transient characteristic. .

In most of optimal design procedure, performance criteria should be defined first. To get this performance criteria, analytic method is preferred. But in case of HVDC inverter since circuit equation is varied depending on the ON-OFF state of each thyristor switch, establishing analytic model is almost impossible. Therefore in most cases simulation is used.

In this paper per phase equivalent circuit is proposed, which can be used in performance calculation such as voltage harmonics.

Per phase equivalent circuit is shown in Fig. 4

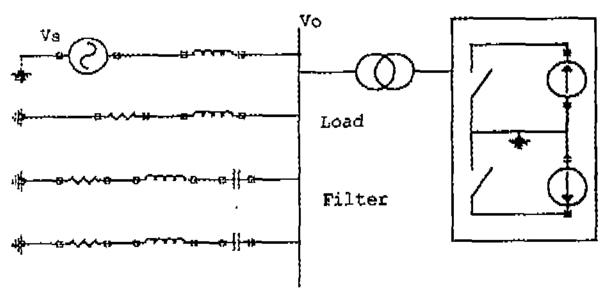

Fig. 4 Per Phase equivalent circuit

Characteristics of proposed equivalent circuit is as follows.

1) Thyristor converter is represented as a current source and depending on the gate pulse it supplies $+I_{dc}$, $-I_{dc}$ or 0, Gate pulse is determined by the delay angle and commutation overlap angle is neglected.

- Upper thyristor ON : $+I_{dc}$
- Lower thyristor ON : $-I_{dc}$
- Both thyristor OFF : 0

2) AC system is considered as voltage source and load is represented as series RL circuit.
3) Tuned filter is used. In case of 12 pulse converter, it represents 11th and 13th harmonic filter.

5.2 System characteristic

Voltage and current waveform of system shown in Fig. 1 is simulated with proposed equivalent circuit. System parameter used in this simulation is shown in Table. 1

Table. 1 System parameters

V_s	141 KV
I_{dc}	1667A
load	*R=100Ω, L=88.0 mH*
11-th filter	R=1.0Ω, L=50mH, C= 1.163 uF
13-th filter	R=1.0Ω. L=53.5mH, C=0.778uF
delay angle	117.5°

In simulation ACSL(Advance Continuos Simulation Language) is used. In Fig. 5, Infinite bus voltage and load voltage is shown. Phase shift between two voltages agrees with the load flow calculation which is about 5° .

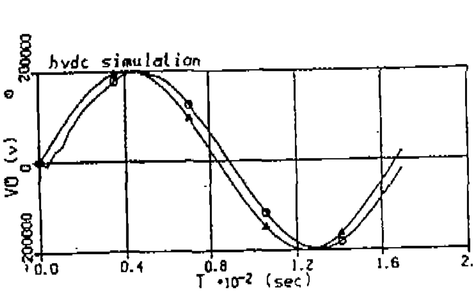

Fig. 5 Infinite bus voltage and load voltage

In Fig. 6 and 7 shows the infinite voltage and load voltage for the different filter parameters with the same tuned frequency.

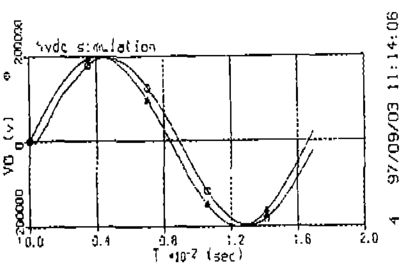

Fig. 6 Infinite bus voltage and load voltage

(L=55mH, C=1.0573uF)

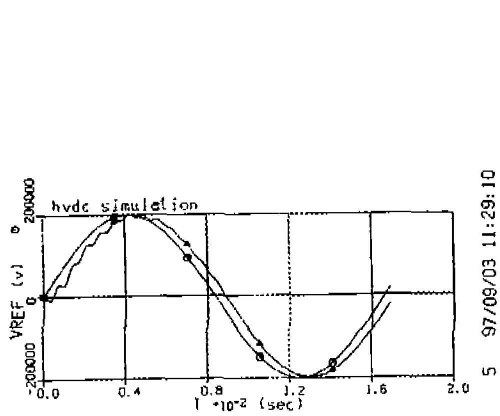

Fig. 7 Infinite bus voltage and load voltage

(L=48mH, C=1.2113uF)

6. Filter parameter optimization

Voltage harmonics and filter power loss are selected as performance index. Once performance index is selected, optimization procedure shown in Fig. 8 can be used.

If the filter parameter is changed, voltage harmonics are also changed. Calculation of voltage harmonics can be easily done with the proposed equivalent circuit. It also effects on the performance of controller.

Voltage difference between detected voltage and infinite bus voltage is

$$e = V_o - V_s \qquad (30)$$

Voltage harmonics can be defined as follows.

$$\varepsilon = E(e^2) = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\alpha+2\pi} e^2 d(wt)} \qquad (31)$$

Equ. (31) is used as a performance criteria for the optimization.

Search direction for the optimization is defined as follows.

$$\nabla = (\varepsilon_{k+1} - \varepsilon_k)/(L_{k+1} - L_k) \qquad (32)$$

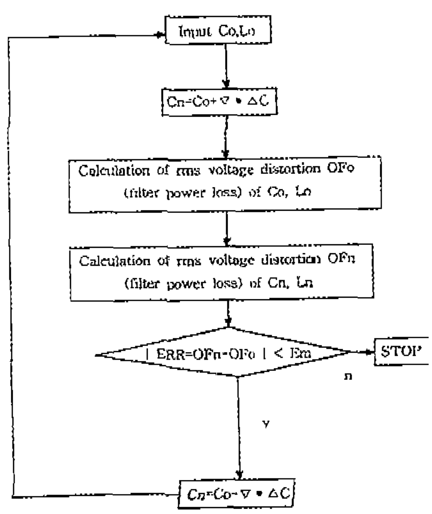

Fig. 8. Flow chart for filter optimization

In Fig. 9, variation of voltage harmonics as a function of filter capacitor is shown. It is found that voltage hormonic is decreased as filter capacitance is increased with same resonant frequency.

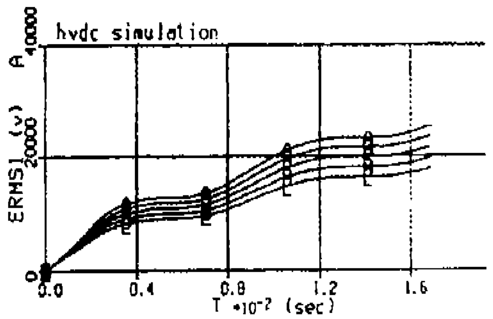

Fig. 9 Variation of Voltage harmonics

In Fig. 10 Variation of filter power loss as a function of filter capacitor is shown. In this figure, filter power loss is defined in equ. (23).
Power loss is calculated simultaneously during simulation and search direction is depending on the variation of power loss.

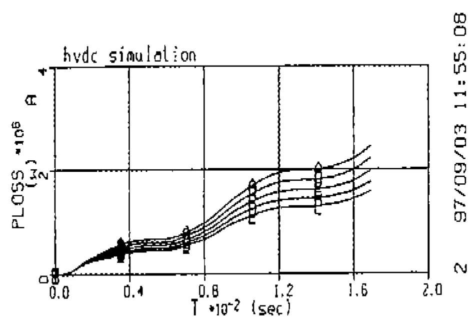

Fig. 10. Variation of power loss

7. Conclusion

For the stable HVDC inverter operation, voltage harmonic of load voltage should be minimized. In most of cases passive filter is used to reduce voltage harmonic. To determine filter parameter, conventional method is used to get harmonics component and optimal value which minimizes voltage harmonic. On the other hand can be determined. Power loss of filter should be considered for the economical reason.

For the optimal filter design voltage harmonic and power filter power loss are selected as a performance index. But analytic calculation of performance index is almost impossible due to switching nature of inverter. In this paper, to analyze system characteristic per phase equivalent circuit is used.

For the performance simulation of equivalent circuit ACSL(Advanced Continuous Simulation Language is used. Optimization procedure is also performed with ACSL.

Performance index such as voltage harmonics and power loss can be calculated as parameter changes and optimization procedure can be applied with per phase equivalent circuit. Optimal filter parameters are obtained.

Application of proposed method to multi bus system is needed for the further research.

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